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DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

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STEELS FOR LARGE SOLID-PROPELLANT ROCKET-MOTOR CASES

by

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to

OFFICE OF THE DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
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SUMMARY

Over the past few years, several alloy steels that have been used for other applications requiring service at high strength levels have come into prominence for use in large solid-propellant rocket-motor cases. Of particular interest for current rocket-case applications are AISI 4340, AMS 6434 (modified), Ladish D-6ac, and H-11 hot-work tool steel. For example, experience at Douglas Aircraft Company has indicated that AISI 4340 steel, fabricated by rolling and welding and heat treated to 260,000 to 280,000 psi tensile strength, is entirely satisfactory for the first and second stages of the Nike Zeus missile. As with other motor-case producers, a period of "learning" and improving on the production and inspection procedures was required before the know-how was gained to produce satisfactory cases. Modified AMS 6434 steel has been specified for the first and second stages of the A-1 Polaris and for the first stage of the A-2 Polaris missiles. In making first-stage Minuteman cases, Allison Division of General Motors Corporation has used D-6ac steel which is a consumable-electrode arc vacuum-melted version of Ladish D-6a steel. Cases for the first and second stages of the Pershing missile have been made of H-11 steel by Pratt and Whitney.

Treatments and properties of the above steels and other alloy steels that are being used or considered for rocket-motor cases are discussed in this report.

Because of the importance of achieving minimum weight for the inert parts in all stages of each rocket system, the specifications require heat treatment of the alloy steel cases to relatively high strength levels. The object is to obtain the highest strength in the steel cases consistent with adequate toughness so they will withstand the design pressures along with other service requirements and still have minimum inert weight. The design and fabrication should be such that the stresses caused by internal pressurizing are as uniform as possible. The inspection techniques should be capable of detecting all flaws larger than normal inclusions. These requirements have led to considerable research and development on high-strength sheet steels and methods for evaluating them. In addition, there has been considerable study of design parameters to obtain more uniform stresses in the structures.

Improved techniques also were required for locating small flaws which can cause failure at low nominal stress levels. Many of the early cases on the Polaris program failed during hydrotesting at nominal stresses much lower than the design burst stresses because of flaws in the welds or of other factors which caused stress concentrations.

Even though there has been considerable advancement in the technology of high-strength sheet steels over the past few years, a continued research effort is warranted in many areas as discussed in other parts of this report.

HIGH-STRENGTH STEELS FOR ROCKET-CASE APPLICATIONS

Table 1 lists the compositions of the main high-strength alloy steels, other than stainless steels, that have been considered for rocket-motor cases. AISI 4130 steel (and 4135) of the chromium-molybdenum type has been used extensively for small solid-propellant rockets that do not require materials of the high strength levels preferred for the larger cases. The remaining steels in the low-alloy-steels group in Table 1 are all nickel-chromium-molybdenum types. AISI 4340 steel is well known for its high hardenability and its high strength properties resulting from standard quenching and tempering treatments. Prior to its use in high-strength rocket cases, this steel was used primarily in highly stressed forgings such as aircraft crankshafts, connecting rods, and landing-gear assemblies. Thus, considerable experience has been gained with this steel over a period of many years.

AMS 6434 steel is a modification of the AISI 4340 type and contains vanadium. The vanadium addition tends to raise the coarsening temperature of the austenite so the microstructure of the heat-treated steel is relatively fine grained.

Ladish D-6a steel has higher carbon content, less nickel and vanadium, and more chromium and molybdenum than AMS 6434 steel. The increased carbon permits higher maximum strengths in the heat-treated steel than would be possible with lower carbon contents. However, the higher carbon also tends to decrease the fracture toughness as compared with a lower-carbon steel at the same strength level. Thus, control of the carbon content to balance the required strength and toughness of the steel in the heat-treated condition is a critical factor in selecting steels for service at high strength levels.

Increased chromium and molybdenum contents over the base AISI 4340-steel type normally require higher austenitizing temperatures. The usual austenitizing temperature for 4340 steel prior to oil quenching is 1550 F. Several hardening treatments have been used for D-6a steel. These include quenching from 1650 F or quenching from 1550 F after a prior treatment at 1650 F (see Table 4, page 12). The lower austenitizing temperature prior to quenching is preferred to minimize distortion. The hardenability of the D-6a steel is such that large cases may be quenched in salt at 400 F to stabilize the temperature at this level before complete transformation to martensite, which occurs on further cooling in air to room temperature. This treatment causes less distortion than is obtained with direct oil quenching to room temperature.

Furthermore, the molybdenum and chromium contents of D-6a are high enough to retard the tempering effect during tempering, thus permitting higher tempering temperatures than can be used to produce the same strength level in AISI 4340 or AMS 6434 steel. Higher tempering temperatures are desirable from the standpoint of relief of residual stresses and improvement in die straightening during tempering. In addition, the molybdenum content of D-6a is sufficient to minimize temper embrittlement.

Ladish D-11 alloy is similar in composition to D-6a except that it has higher molybdenum and vanadium contents. It has been considered for future rocket cases. Only limited data are available on sheet material of this alloy.

TABLE 1. ALLOY STEELS CONSIDERED FOR EXPERIMENTAL AND PRODUCTION SOLID-PROPELLANT ROCKET CASES

Steel Designation	Composition, per cent									
	C	Mn	P(a)	S(a)	Si	Ni	Cr	Mo	V	Other
					Low Alloy Steels					
AISI 4130	0.28-0.33	0.40-0.60			0.20-0.35	--	0.80-1.10	0.15-0.25	--	
AISI 4340	0.38-0.43	0.60-0.80	0.015	0.015	0.20-0.35	1.65-2.00	0.70-0.90	0.20-0.30	--	
AMS 6434	0.31-0.38	0.60-0.80	0.015	0.015	0.20-0.35	1.65-2.00	0.65-0.90	0.30-0.40	0.17-0.23	
AMS M255	0.33-0.38	0.60-0.90	0.015	0.015	0.40-0.60	1.65-2.00	0.65-0.90	0.30-0.40	0.17-0.23	
Ladish D-6a(b)	0.42-0.48	0.60-0.90	0.015	0.015	0.15-0.30	0.40-0.70	0.90-1.20	0.90-1.10	0.05-0.10	
Ladish D-11	0.42-0.48	0.60-0.90			0.15-0.30	0.40-0.70	0.90-1.20	1.90-2.10	0.45-0.55	
					High-Silicon Alloy Steels					
300-M	0.41-0.46	0.65-0.90	0.015	0.015	1.45-1.80	1.65-2.00	0.70-0.95	0.30-0.45	0.05 min.	0.04-0.10Al
MBMC No. 1	0.42-0.46	0.70-0.90	0.015	0.015	1.50-1.70	--	0.60-0.90	--	0.10 min.	
Airsteel X-200	0.43	0.85	0.015	0.015	1.50	--	2.00	0.50	0.05	
4330V (Mod + Si)	0.30-0.35	0.75-1.0			1.40-1.70	1.50-2.00	0.80-1.00	0.40-0.60	0.08-0.12	
UHS-260	0.35	1.25			1.85	--	1.25	--	0.20	0.35W
Labelle HT	0.45	1.35			2.30	--	1.40	0.40	0.30	
S5A (Mod.) (G.E.)	0.47-0.52	0.80			1.80	--	--	0.50	0.25	
					Silicon-Cobalt Steels					
4137Co (UCX-2)	0.39	0.70	0.015	0.012	1.00	--	1.10	0.25	0.15	1.00Co
Rocoloy 270	0.39-0.45	0.40-0.80	0.01	0.01	0.90-1.30	0.75-1.10	1.15-1.60	0.40-0.60	0.1-0.2	0.25-0.4W, 1.2-1.5Co
					Hot-Work Steels					
AISI H-11	0.30-0.40	0.20-0.40	0.015	0.015	0.80-1.20	--	4.75-5.50	1.25-1.75	0.30-0.50	
Peerless 56	0.38-0.44	0.40-0.70	0.015	0.015	0.80-1.20	--	3.00-3.60	2.00-2.75	0.25-0.50	
					High-Nickel Maraging Steels					
18Ni (250)(c)	0.02	0.10 max	0.01 max	0.01 max	0.10 max	18	--	5	--	7.0Co, 0.4Ti, 0.1Al
18Ni (300)(c)	0.02	0.10 max	0.01 max	0.01 max	0.10 max	18	--	5	--	9.0Co, 0.6Ti, 0.1Al
20Ni(c)	0.02	0.15 max	0.01 max	0.01 max	0.15 max	20	--	--	--	0.5Cb, 1.4Ti, 0.2Al

(a) Maximum P and S if steel is to be welded (total P + S 0.025 max).
(b) Allison prefers D-6a with 0.45-0.50C and 0.08-0.15V.
(c) Added: 0.003B, 0.02Zr, and 0.05Ca.

From 1 to 2 per cent of silicon in alloy steels retards the tempering effect and raises the 550 F embrittlement temperature. For this reason, relatively high strengths are achieved without embrittlement when the high-silicon steels are tempered from 550 to 700 F. Tempering in this range permits greater stress relief than is obtained at 425 F, which is often used for AISI 4340 steel for high-strength service. The most prominent high-silicon alloy steels that have been considered for rocket cases are listed in the second group in Table 1. Each of these steels was developed for use at high strength levels. Austenitizing temperatures for these steels are in the range from 1575 to 1750 F. They have been hardened by quenching in air, molten salt at 400 F, or oil, depending on the section size and other factors. In welded construction, there has been some indication that the high-silicon alloy steels tend to develop small cracks in the welds. However, General Electric Company has used 300-M steel for rocket cases which require only girth welds. Low-silicon filler wire is used to minimize the cracking tendency. Welding of these steels needs to be studied further because present data are limited.

Several other steels containing about 1.0 per cent silicon and also 1.0 to 1.5 per cent cobalt have been developed for high-strength rocket cases at Mellon Institute. Compositions of these steels are shown in the third group in Table 1. The carbon and silicon contents as well as the alloy additions have been intentionally balanced to achieve good toughness, high strength, and good weldability. The cobalt addition reportedly promotes fine grain structure in the heat-treated steel. In developing these steels, burst tests, pressure-vessel tests, and one or more developmental rocket cases were used for evaluation studies.

Another class of steels that has been considered for rocket-case applications is the hot-work die steels. These steels can be heat treated to high strength levels and have sufficient hardenability to harden by air or inert-gas quenching. They exhibit secondary hardening during tempering. Austenitizing temperatures are usually in the range from 1900 to 1950 F, and tempering temperatures are usually in the range from 1000 to 1100 F. The high tempering temperature tends to promote relief of residual stresses. Welding of the high-chromium hot work steels requires very close control of preheat and postheat operations to minimize weld cracking and distortion. This has been done satisfactorily on girth welds of Pershing missile cases in which the cylindrical section is produced by power-roll forming. However, longitudinal welds on developmental cases of H-11 steel have resulted in considerable distortion which would be a serious problem in cases too large to produce by power-roll forming.

Of the hot-work die steels, current effort has been concentrated on the H-11 type. It is being heat treated to somewhat higher yield-strength levels than the lower alloy steels. There are a number of modifications and trade names for the hot-work steels not shown in Table 1.

The high-nickel Mar-Aging steels are a new class with very low carbon content, high nickel content, cobalt, and other alloy additions. The compositions of the three types that are of interest for high-strength rocket cases are noted in the last section of Table 1. The hardening reaction is rather complex, but the heat-treatment produces a low-carbon martensitic matrix which is hardened by a precipitation mechanism during maraging. The final treatment after forming, welding, etc., consists only of maraging at 850 or 900 F, and quenching is not necessary. It has been reported that these steels can be welded satisfactorily and have adequate fracture toughness at high strength levels.

Yield strengths of approximately 280,000 psi can be achieved with the 18Ni-9Co-0.5Ti type. Because of these advantages, the Mar-Aging steels are being considered for very large rocket cases which must be fabricated by the roll-and-weld techniques and which are too large for heat treating in the largest available austenitizing furnaces. Much work, however, remains to be done before the full potential of these new steels will be established.

Several of the heat-treatable stainless steels have also been considered for rocket-case applications. However, in reviewing these steels for rocket-case programs, engineers at the Budd Company[1]* and others have indicated that they can be considered only when used with special fabrication techniques. The stainless steels of the highest strength levels acquire their strength by a combination of cold working and heat treatment. Fusion welding causes softening in the heat-affected zone, and the high strength cannot be recovered by further heat treatment. Furthermore, it has been noted that the heat-treatable stainless steels at their highest strength levels have relatively low fracture toughness (except when produced in relatively thin sheet).

One experimental fabrication technique that is in the development stage at Borg-Warner and adaptable to stainless steel strip is the formation of cylindrical sections by spiral wrapping two layers of steel strip on a mandrel so that the spiral joints are staggered.[2] An adhesive strip is interwrapped between the two steel strips. Curing of the adhesive at elevated temperatures and under pressure from a special mandrel results in bonding of the two layers of strip. AM 355 stainless steel strip cold rolled and tempered to a tensile strength between 350,000 and 360,000 psi has been used in the development program.

Another experimental fabrication technique that has been used for austenitic stainless steels is cryogenic stretch forming.[3,4] In this process, a roll-and-welded preform is made of annealed austenitic stainless steel such as Type 301. The preform is cooled to -320 F in liquid nitrogen and pressurized to cause plastic expansion in a die. The plastic deformation results in a substantial increase in the properties of the material.

These special fabrication methods adapted to the stainless steels do not require welding of the metal after the optimum properties are obtained. Up to the present time, they have been used only for relatively small pressure vessels.

REVIEW OF MECHANICAL PROPERTIES OF HIGH-STRENGTH STEELS

Data on the tensile properties of high-strength steels as sheet specimens heat treated to high strength levels and representing various melting procedures, heat treatments, etc., have been available only in the last few years. For this reason, data on tensile properties of a number of the alloys listed in Table 1 are included in this section. Effects of tempering temperature, direction of specimen in the sheet, melting practice, quenching procedure, and other factors on the tensile properties are illustrated in the tables discussed in the following paragraphs.

*Numbers refer to references listed at the end of the report.

Yield strength-density ratios and tensile strength-density ratios are also given in the tables in order to have a common basis for comparing the strength values. Certain goals for the strength-density ratios of rocket-case materials are often mentioned, e.g., 1,000,000-inch tensile strength-density ratio. The ratios given in the tables will aid in evaluating the steels on this basis. Compositions of the steels and the heat treatments are also noted in the tables to provide as much information as possible. Only limited information on the degree of decarburization is given, although this is an important variable which is often neglected or improperly assumed to be negligible.

Furthermore, data from several sources are given for each alloy to provide a broader view of the tensile properties that can be expected.

In Table 2, it will be noted that the yield strength for 4340 steel, oil quenched and then tempered at 425 F, is slightly over 200,000 psi. This is in the tempering temperature range usually used for motor cases of this steel. Thus, yield strength-density ratios of 700,000 to 800,000 inches can be achieved with this steel (or tensile strength-density ratios of 890,000 to 990,000 inches). The data show no marked differences in properties between longitudinal and transverse specimens or between air-melted, vacuum-melted, and consumable-electrode vacuum-arc-melted material. Effects of these variables are seldom noticed in unnotched tensile data. However, effects of melting procedure and specimen orientation are usually evident in results of sharp-notched tensile tests and in fracture toughness data which are not included in this report.

The tensile properties of AMS 6434 steel, as shown in Table 3, are much the same as for corresponding specimens of AISI 4340 steel, as would be expected from the similarity in compositions.

Tensile properties of sheet specimens of D-6a steel are shown for a range of tempering temperatures in Table 4. The maximum tensile strengths that can be obtained with this steel are slightly higher than for AISI 4340 or AMS 6434 steel because of the higher carbon content. The yield strengths at the lower tempering temperatures are comparable, but the D-6a steel retains higher yield and ultimate strengths after tempering at the higher tempering temperatures, e.g., from 600 to 950 F. This is the range of tempering temperatures used for pressure vessels and motor cases of D-6ac steel. Thus, the yield strength-density ratios are from about 700,000 to 780,000 inches for this steel (or tensile strength-density ratios from about 750,000 to 900,000 inches). A tempering temperature of 950 F is usually used for D-6ac cases to achieve a suitable balance of strength and toughness.

Tensile properties of D-11 steel sheet specimens are reported to be 235,000 psi yield strength, 255,000 psi tensile strength, and 8 per cent elongation. These properties are achieved by a proprietary treatment developed at Allison. Quenching is in salt at 400 to 425 F and final tempering is at 1050 F.

Of the high-silicon alloy steels, Type 300-M is probably the best known (formerly Tricent). This steel is normally hardened by austenitizing at 1575 F, oil quenching, and tempering at 600 F. As indicated in Table 5, this treatment usually results in a yield strength of about 230,000 psi and a tensile strength of 270,000 to 280,000 psi. These values are somewhat higher than the corresponding values for AISI 4340 steel. The balance of carbon content, silicon, and other alloying elements has a marked effect on the properties of this alloy. This is probably why the specimens referenced by (c) in Table 5 have higher strengths for the 600 F tempering temperature.

TABLE 2. TENSILE PROPERTIES OF AISI 4340 STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			0.10-Inch Sheet[a]			
Longitudinal Specimens						
400	230	280	8.5		813	990
600	216	241	6.0		764	852
800	196	209	7.0		693	740
1000	166	175	10		586	620
Transverse Specimens						
400	221	276	7.5		782	975
600	215	245	6.0		760	867
800	199	210	6.5		704	742
1000	167	175	9.0		590	620
			Air Melted 0.080-Inch Sheet[b]			
Longitudinal Specimens						
350	208	264	7.0	52	735	933
425	204	250	6.0	50	721	884
500	198	237	6.5	48	700	838
700	182	204	6.0	44	643	720
Transverse Specimens						
350	215	275	6.0	52	760	972
425	205	253	6.0	50	725	895
500	204	245	4.5	49	720	865
700	184	210	4.5	45.5	650	743
			Vacuum Melted 0.090-Inch Sheet[c]			
Longitudinal Specimens						
425	214	266	7.0	49	757	940
500	206	252	7.0	49	728	890
700	186	215	6.5	42	658	760
Transverse Specimens						
425	216	268	6.5	51	763	947
500	208	252	6.0	49	735	890
700	187	218	6.5	43	662	770
			CEVA Melted 0.080-Inch Sheet[d]			
Longitudinal Specimens						
350	220	280	7.0	54	778	990
425	211	260	6.5	52	746	918
500	201	244	6.5	50.5	710	862
700	186	215	6.0	47.5	658	760
Transverse Specimens						
350	220	280	7.0	54	778	990
425	211	259	6.5	52	746	915
500	203	246	7.0	51	718	870
700	187	213	6.0	47	662	753

TABLE 2. (Continued)

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
Longitudinal Specimens		Air Melted 0.095-Inch Sheet, Oil Quenched(e)				
400	214	265	8.3	50	756	937
500	208	245	7.2	48	735	866
600	206	233	6.2	47.5	728	824
700	196	215	6.2	45	693	788
800	186	196	6.5	42.5	660	693
900	174	180	8.2	40.5	615	636
1000	160	165	10.0	37.5	565	583
Longitudinal Specimens		Air Melted 0.095-Inch Sheet, Salt Quenched 400 F for 5 Min.(e)				
400	200	268	9.0	51	707	948
500	208	250	6.3	49.5	735	884
600	205	236	6.3	47.5	725	834
700	195	216	6.5	45	690	763
800	182	195	7.0	42	667	690
900	173	182	8.3	40	622	644
1000	159	165	11.0	36	562	583

Note: Density 0.283 lb/in.^{3}.

(a) 1525 F 1 hr, OQ, temper 1 hr; 0.40C, 0.83Mn, 0.21Si, 0.72Cr, 1.77Ni, 0.26Mo.(5)

(b) 1575 F 40 min, OQ, temper 2 + 2 hr; 0.38C, 0.54Mn, 0.21Si, 0.011P, 0.026S, 0.77Cr, 1.45Ni, 0.25Mo, 42 ppm N_2, 41 ppm O_2, 2.7 ppm H_2.(6)

(c) 1575 F 40 min, OQ, temper 2 + 2 hr; 0.40C, 0.70Mn, 0.28Si, 0.011P, 0.005S, 0.89Cr, 1.93Ni, 0.20Mo, 0.06V.(6)

(d) 1575 F 40 min, OQ, temper 2 + 2 hr; 0.40C, 0.43Mn, 0.17Si, 0.011P, 0.005S, 0.84Cr, 1.95Ni, 0.25Mo, 9 ppm N_2, 12 ppm O_2, 1.2 ppm H_2.(6)

(e) 1500 F salt 20 min, oil or salt quench, temper 2 hr; 0.40C, 0.75Mn, 0.009P, 0.007S, 0.30Si, 1.75Ni, 0.75Cr, 0.22Mo, 0.02Al.(7,8)

TABLE 3. TENSILE PROPERTIES OF AMS 6434 (MODIFIED) STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			Air Melted 0.109-Inch Sheet[a]			
Longitudinal Specimens						
400	219	266	7.5	50	774	940
500	216	247	7	48	763	873
725	207	225	6.5	46	732	795
Transverse Specimens						
400	210	268	6	51	743	948
500	213	250	6	51	755	884
725	211	228	6	46	745	806
			Vacuum Melted 0.090-Inch Sheet[b]			
Longitudinal Specimens						
400	206	252	7	49	728	891
500	208	238	6	47	735	842
725	194	218	6	45	686	770
Transverse Specimens						
400	206	255	5.5	49.5	721	900
500	202	240	5.5	47	714	850
725	195	217	6	45	690	767
			CEVA Melted 0.080-Inch Sheet[c]			
Longitudinal Specimens						
400	219	266	6	49	774	940
500	221	256	5.5	49	780	905
725	199	218	5.5	42	704	770
Transverse Specimens						
400	221	269	5.5	49	780	950
500	218	257	5.5	48	770	910
725	200	220	5.5	43	707	778
			Air Melted 0.095-Inch Sheet, Oil Quenched[d]			
Longitudinal Specimens						
400	211	260	7.5	49	746	920
500	208	246	6.0	47	735	870
600	203	232	6.8	45	717	820
700	197	219	7.2	46	697	774
800	190	203	6.5	44	672	718
900	182	191	8.3	42	644	675
1000	176	187	10.2	39.5	622	660

TABLE 3. (Continued)

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
	Air Melted 0.095-Inch Sheet, Salt Quenched 400 F 5 Min.(d)					
Longitudinal Specimens						
400	197	261	8.0	47.5	696	925
500	206	243	6.7	45	728	860
600	196	226	6.7	44	693	800
700	192	213	6.3	42	680	753
800	194	198	7.5	40.5	685	700
900	180	192	8.2	42	636	680
1000	173	184	10.3	39.5	611	650

Note: Density 0.283 lb/in.^{3}.

(a) 1575 F 20 min, OQ, temper 2 hr; 0.36C, 0.73Mn, 0.019P, 0.015S, 0.33Si, 1.78Ni, 0.86Cr, 0.31Mo, 0.19V.[9]
(b) 1575 F 40 min, OQ, temper 2 hr; 0.35C, 0.67Mn, 0.30Si, 0.010P, 0.007S, 0.90Cr, 1.93Ni, 0.33Mo, 0.20V.[10]
(c) 1575 F 40 min, OQ, temper 2 hr; 0.37C, 0.39Mn, 0.46Si, 0.010P, 0.005S, 0.92Cr, 1.67Ni, 0.30Mo, 0.20V, 26 ppm N_2, 4 ppm O_2, 1.3 ppm H_2.[6]
(d) 1625 F salt 30 min, oil or salt quench, temper 2 hr; 0.36C, 0.74Mn, 0.008P, 0.008S, 0.28Si, 1.72Ni, 0.76Cr, 0.33Mo, 0.20V, 0.03Al.[11]

TABLE 4. TENSILE PROPERTIES OF LADISH D-6a STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			Air Melted 0.100-Inch Sheet[(a)]			
Longitudinal Specimens						
600	251	275	5.0		887	972
700	243	259	5.0		860	915
800	230	237	6.0		814	838
900	225	236	7.5		795	834
1000	205	219	9.5		725	774
1100	186	191	8.0		657	675
Transverse Specimens						
600	255	279	4.5		900	985
700	228	249	5.5		805	880
800	224	236	6.0		790	835
900	214	219	8.0		757	775
1000	210	220	10.0		742	778
1100	192	201	7.5		680	710
			0.110-Inch Sheet[(b)]			
Transverse Specimens						
400	228	300	8.0		806	1060
600	220	259	6.5		778	915
800	206	230	7.0		730	815
1000	196	212	9.0		693	750
			CEVA Melted (D6ac) 0.072-Inch Thick Specimens Quenched in Salt at 400 F[(c)]			
400	208	287	8	52	735	1010
450	224	277	7	51.5	792	980
500	229	271	6	50	810	960
550	225	261	5.5	50	795	922
600	221	254	5.5	49	780	898
650	218	249	5.5	48	770	880
700	208	235	5.5	46	735	830
750	212	235	6	46	750	830
800	209	229	6	45	740	810
850	208	224	6.5	45	735	792
900	199	213	7	44	704	753
950	200	214	8	44	706	756
1000	195	207	8.5	44	690	733
			D6ac, Minimum Properties (Allison)[(d)]			
950	195	228	7		690	805

Note: Density 0.283 lb/in.^{3}.

(a) Normalize 1650 F, austenitize 1550, air quench, surface layers removed after heat treating.[(12)]

(b) Normalize 1650 F 40 min, austenitize 1550 F 1 hr, OQ, temper 1 hr; 0.42C, 0.79Mn, 0.27Si, 1.12Cr, 0.58Ni, 0.98Mo.[(5)]

(c) D6ac ground from 0.625-inch plate; 1650 F 30 min, cool to 1550 F held 30 min, salt Q 400 F 5-7 min, AC, temper 2 hr, 0.006 in, partial decarb. both surfaces.[(13)]

(d) 1650 F 1 hr, salt Q 400 5 min, AC, 950 F 4 hr; 0.45-0.50C, 0.08-0.15V.[(14)]

TABLE 5. TENSILE PROPERTIES OF 300-M STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			Air Melted 0.109-Inch Sheet[a]			
Longitudinal Specimens						
600	231	279	7	53	826	1000
800	189	246	8	48.5	675	880
Transverse Specimens						
600	232	279	5.5	52	830	1000
800	190	249	7	48.5	680	890
			Air Melted 0.080-Inch Sheet[b]			
Longitudinal Specimens						
500	211	275	7.5	53	753	982
600	233	272	5.5	53	832	972
700	177	238	7.0	49.5	632	850
900	188	222	7.5	47.5	672	793
Transverse Specimens						
500	211	273	7.0	52.5	755	975
600	216	257	5.0	52.5	772	917
700	173	231	7.0	48.5	618	825
900	188	222	7.5	47.5	670	793
			Vacuum Melted 0.090-Inch Sheet[c]			
Longitudinal Specimens						
600	244	297	6.5	53.5	872	1060
Transverse Specimens						
600	245	296	5.5	53.5	875	1060
			CEVA Melted 0.080-Inch Sheet[d]			
Longitudinal Specimens						
500	226	279	6.5	47	808	1000
600	231	277	6.5	50	825	990
800	189	232	6.5	44	675	828
900	188	217	6.5	42	672	775
Transverse Specimens						
500	228	283	6.5	48	815	1010
600	231	278	6.5	50	825	992
800	195	238	7.0	45	696	850
900	191	220	7.0	43	683	785

Note: Density 0.280 lb/in.^{3}.

(a) 1575 F 30 min, OQ, temper 2 hr; 0.43C, 0.86Mn, 0.015P, 0.031S, 1.35Si, 1.88Ni, 0.86Cr, 0.30Mo.(9)

(b) 1575 F 40 min, AQ, temper 2 + 2 hr; 0.40C, 0.82Mn, 1.57Si, 0.012P, 0.013S, 0.88Cr, 1.84Ni, 0.23Mo, 0.24V, 103 ppm N_2, 26 ppm O_2, 2.3 ppm H_2.(6)

(c) 1575 F 40 min, OQ, temper 2 + 2 hr; 0.43C, 0.74Mn, 1.57Si, 0.009P, 0.005S, 0.91Cr, 1.90Ni, 0.34Mo, 0.09V.(10)

(d) 1575 F 40 min, AQ, temper 2 + 2 hr; 0.41C, 0.51Mn, 1.57Si, 0.011P, 0.006S, 0.82Cr, 1.80Ni, 0.25Mo, 12 ppm N_2, 4 ppm O_2, 1.4 ppm H_2.(6)

The tensile specimens of MBMC No. 1 steel used in obtaining data for Table 6 had higher yield strengths than specimens of 300-M steel tempered at corresponding temperatures. This is in part the result of slightly higher carbon. Apparently, however, MBMC No. 1 tends to have insufficient fracture toughness for rocket-case applications.

Airsteel X-200 has higher chromium and molybdenum contents than the 300-M steel. The larger amounts of these elements tend further to retard the tempering effect in this steel. Consequently, the specimens of X-200 steel have higher strengths at a given tempering temperature, in the range from 600 to 1000 F, than do corresponding specimens of 300-M steel. Specimens and components of Airsteel X-200 are normally air quenched. When tempered at 700 F, they have yield strengths over 230,000 psi or yield strength-density ratios over 820,000 inches as shown in Table 7. Use of lower tempering temperatures is avoided because of brittleness.

Tensile properties of sheet specimens of S5A (modified) by G. E. are 275,000 psi yield strength and 310,000 psi tensile strength. A 1650 F austenitizing treatment and double temper at 600 F are used in achieving these properties.

The tensile properties of 4137 Co and Rocoloy 270 steels (silicon-cobalt alloy types) are presented in Table 8. These steels are normally tempered at 550 or 600 F after quenching in oil or in molten salt at 400 F. It will be noted that the yield strengths of the 4137 Co steel specimens tempered in this temperature range are about 250,000 psi with a yield strength-density ratio of about 900,000 inches.

Sheet specimens of Rocoloy 270, oil quenched and tempered at 600 F, have a yield strength of 270,000 psi with a yield strength-density ratio of 968,000 inches.

In Table 9, it will be noted that yield strengths of 230,000 to 240,000 psi can be achieved in sheet specimens of H-11 steel after austenitizing at 1900 F, air quenching, and tempering at 1000 F. The corresponding yield strength-density ratios are from 820,000 to 860,000 inches. Reference is often made to the fact that this steel has a tensile strength-density ratio over 1,000,000 inches in sheet form when tempered at 1000 F. This is illustrated in the column at the far right in Table 9. The tensile data on unnotched specimens show no appreciable differences in properties for corresponding specimens from longitudinal and transverse directions in the sheet or between air-melted and consumable-electrode vacuum-arc-melted material.

The tensile data for Peerless 56 steel, as shown in Table 10, are comparable to those for H-11 steel. Peerless 56 steel has less chromium and more molybdenum than the H-11 or 5-chromium type. Specimens of Peerless 56 steel tempered at 1000 F have yield strengths between 230,000 and 260,000 psi with ultimate strengths over 300,000 psi. Thus, tensile strength-density ratios over 1,000,000 can be obtained for this steel also. However, there has been considerably less experience gained in using this steel than with the H-11 type.

Because of the attractive properties that can be achieved in the 18 per cent nickel Mar-Aging steels with a 900 F aging treatment, these steels are being subjected to preliminary evaluation tests for large rocket cases. Representative properties for both the 18 and 20 per cent nickel types are shown in Table 11. The 18 Ni (300) type has a yield strength of 280,000 psi and a yield strength-density ratio of 970,000 inches after the

TABLE 6. TENSILE PROPERTIES OF MBMC NO. 1 OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			0.05-Inch Sheet[a]			
Transverse Specimens						
550	247	281	4.0		882	1000
650	241	271	4.0		861	968
750	236	257	4.5		842	918
850	201	209	5.0		718	746
			0.100-Inch Sheet[b]			
Longitudinal Specimens						
700	246	278	6	54	880	993
750	228	259	7	52	815	925
800	215	236	7	49	768	844
900	186	206	8	46	665	736
Transverse Specimens						
700	242	272	4.5	53	865	972
750	226	259	5.5	51.5	808	925
800	209	233	6	48	747	832
900	187	205	7.5	46	668	732

Note: Density 0.280 lb/in.^{3}.

(a) 1600 F 1 hr, OQ, temper 1 hr; 0.45C, 0.81Mn, 1.52Si, 0.80Cr, 0.17Ni, 0.07Mo.[5]

(b) 1725 F 40 min, OQ, temper 2 hr; 0.43C, 0.98Mn, 1.47Si, 0.14P, 0.015S, 0.73Cr, 0.09Ni, 0.03Mo, 0.04V, 0.005Al.[15]

TABLE 7. TENSILE PROPERTIES OF AIRSTEEL X-200 STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
Air Melted 0.060-Inch Sheet(a)						
Longitudinal Specimens						
400	218	312	9		772	1110
500	235	295	7		840	1050
600	238	290	7		850	1040
700	242	285	7		885	1020
800	223	270	10		798	964
1000	203	237	8		725	846
Air Melted 0.105-Inch Sheet(b)						
Longitudinal Specimens						
700	235	287	6	52.5	840	1020
800	208	270	9	51	744	965
Transverse Specimens						
700	237	275	1.5	53	847	982
800	215	264	5	51	768	942
Air-Melted 0.080-Inch Sheet(c)						
Longitudinal Specimens						
700	233	281	6	54	832	1000
800	208	266	5.5	53	743	950
1100	171	202	9	44	811	722
Transverse Specimens						
700	242	292	4.5	57	865	1040
800	212	275	5.5	53	758	982
1100	176	206	9.5	45	630	735
Vacuum Melted 0.090-Inch(d)						
Longitudinal Specimens						
700	233	285	6.5	53	833	1020
800	204	262	7.0	49.5	730	935
1100	178	208	9.0	43	635	743
CEVA Melted 0.080-Inch Sheet(e)						
Longitudinal Specimens						
700	257	310	5.5	55	920	1110
800	220	287	5.0	52	787	1020
1100	189	222	8.0	46	875	793
Transverse Specimens						
700	257	313	4.5	54	918	1120
800	221	291	4.5	52	790	1040
1100	194	226	8.0	45	893	808

Note: Density 0.280 lb/in.^{3}.

(a) 1750 F 15 min, AQ, temper 30 min; 0.40C, 0.97Mn, 0.012P, 0.0105, 1.56Si, 1.95Cr, 0.50Mo, 0.07V.(16)

(b) 1725 F 30 min, AQ, temper 2 hr; 0.44C, 0.93Mn, 0.012P, 0.020S, 1.20Si, 2.22Cr, 0.39Mo, 0.075V.(9)

(c) 1725 F 40 min, AQ, temper 2 hr; 0.40C, 1.03Mn, 1.04Si, 0.012P, 0.0165, 1.92Cr, 0.35Mo, 0.07V, 88 ppm N_2, 12 ppm O_2, 2.2 ppm H_2.(6)

(d) 1725 F 40 min, AQ, temper 2 hr; 0.44C, 0.88Mn, 1.47Si, 0.008P, 0.0075, 1.99Cr, 0.50Mo, 0.09V, 11 ppm N_2, 7 ppm O_2, 1.3 ppm H_2.(6)

(e) 1725 F 40 min, AQ, temper 2 hr; 0.49C, 0.60Mn, 1.77Si, 0.011P, 0.007S, 2.02Cr, 0.80Mo, 0.03V, 15 ppm N_2, 5 ppm O_2, 2.0 ppm H_2.(6)

TABLE 8. ROOM-TEMPERATURE TENSILE PROPERTIES OF 4137 Co AND ROCOLOY 270 STEEL AS SHEET OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			4137 Co 0.095-Inch Sheet(a)			
550 (OQ)	247	287	5.5		895	1025
600 (OQ)	242	274	6.0		877	993
650 (OQ)	237	267	6.0		860	967
650 (Salt)	235	275	6.0		852	995
			4137 Co (MX-2) 0.095-Inch Sheet(b)			
Longitudinal Specimens						
400	236	298	7	56	855	1080
550	256	290	6	55	928	1050
650	247	280	6	55	895	1020
800	213	238	7	49	772	862
1000	201	211	9	46	730	765
Transverse Specimens						
400	253	304	6.5	54	917	1100
550	255	292	5.5	55	924	1060
650	247	279	5.5	55	895	1010
			Rocoloy 270 0.100-Inch Sheet(c)			
400	240	332	7.0	58.5	860	1190
500	266	324	5.3	58	954	1160
600	270	320	5.5	51.5	968	1150
700	265	308	5.3	56	950	1100
800	226	283	6.8	54	810	1010
900	214	278	7.8	53	768	996
1000	232	266	7.3	52	840	953

(a) 4137 Co specimens austenitized at 1700 F for 25 minutes, quenched in oil or in salt at 400 F for 10 minutes, and tempered (density 0.276 lb/in.^{3}).

(b) MX-2 alloy specimens, 1675 F 30 minutes, oil quenched, tempered 1.5 + 1.5 at indicated temperatures; C 0.41, Mn 0.64, Si 0.54, P 0.012, S 0.014, Ni 0.15, Cr 1.23, Mo 0.27, Co 1.03, V 0.22, Al 0.09.[17]

(c) Rocoloy 270 specimens austenitized at 1730 F for 25 minutes, oil quenched, and triple tempered for 1-1/2 hours at indicated temperature (density 0.279 lb/in.^{3}).[18]

TABLE 9. TENSILE PROPERTIES OF TYPE H-11 STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			Air Melted 0.125-Inch Vascojet 1000 Sheet[a]			
Longitudinal Specimens						
1000	241	298	7	54	860	1060
1050	232	283	7	53	830	1010
1100	204	243	9	45	730	870
Transverse Specimens						
1000	247	296	4.5	54.5	883	1060
1050	238	279	6	54	850	1000
			Air Melted 0.080-Inch Sheet[b]			
Longitudinal Specimens						
1000	231	287	5.0		825	1030
1050	204	255	6.5		730	912
1100	175	217	8.5		625	775
Transverse Specimens						
1000	230	288	5.5		822	1030
1050	200	261	6.5		715	932
1100	175	215	8.5		625	770
			CEVA Melted 0.080-Sheet[c]			
Longitudinal Specimens						
1000	228	287	5.5	56.5	815	1020
1050	211	261	7.0	53.5	755	932
1100	174	220	7.5	48.5	622	785
Transverse Specimens						
1000	230	291	5.0	57	822	1040
1050	214	265	6.5	54	765	948
1100	173	220	8.0	48.5	618	785

Note: Density 0.280 lb/in.^{3}.

(a) 1900 F 30 min, AQ, temper 3 + 3 + 3 hr; 0.41C, 0.36Mn, 0.015P, 0.016S, 0.095Si, 5.55Cr, 1.21Mo, 0.53V.[9]

(b) 1900 F 40 min, AQ, temper 3 + 3 + 3 hr; 0.41C, 0.37Mn, 0.80Si, 0.016P, 0.019S, 5.96Cr, 0.57Mo, 0.48V, 29 ppm N_2, 105 ppm O_2, 1.6 ppm H_2.[6]

(c) 1900 F 40 min, AQ, temper 3 + 3 + 3 hr; 0.44C, 0.25Mn, 0.89Si, 0.011P, 0.010S, 5.06Cr, 1.35Mo, 0.78V, 53 ppm N_2, 8 ppm O_2, 1.1 ppm H_2.[6]

TABLE 10. TENSILE PROPERTIES OF PEERLESS 56 STEEL OVER RANGE OF TEMPERING TEMPERATURES

Tempering Temperature, F	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
			0.09-Inch Sheet[(a)]			
Transverse Specimens						
1100	208	244	6.0	48	736	870
1150	164	190	7.5	41	586	680
1200	135	160	10	34	482	572
			Air Melted 0.067-Inch Thick[(b)]			
Longitudinal Specimens						
1000	263	308	6	57	940	1100
1100	220	254	5	51	785	910
Transverse Specimens						
1000	256	311	6	56.5	915	1110
1100	218	255	5.5	50.5	780	910
			Air Melted 0.080-Inch Thick[(c)]			
Longitudinal Specimens						
1000	238	302	5.0	57	850	1080
1020	250	307	5.0	58	893	1100
1100	233	275	5.0	55	833	980
1125	225	260	6.0	53	804	930
Transverse Specimens						
1000	245	314	4.5	58.5	875	1120
1020	255	314	5.0	58	910	1120
1100	238	282	5.0	55.5	850	1010
1125	228	266	5.0	53	815	950
			Vacuum Melted 0.090-Inch Sheet[(d)]			
Longitudinal Specimens						
1020	258	308	5.0	58	922	1100
1050	250	292	6.0	53.5	893	1040
1100	231	267	6.5	52	825	955
Transverse Specimens						
1020	260	307	5.0	54.5	930	1100
1050	260	302	6.0	54.5	930	1080
1100	230	272	6.0	52	822	972
			CEVA Melted 0.080-Inch Sheet[(e)]			
Longitudinal Specimens						
1000	229	305	5.5	58	818	1090
1020	231	303	5.5	57.5	825	1080
1100	226	275	5.5	55.5	808	982
1125	209	255	5.0	53.5	747	910
Transverse Specimens						
1000	233	305	5.5	58	832	1090
1020	234	300	5.5	57.5	838	1070
1100	227	275	5.5	55	810	982
1125	211	255	5.0	53	753	910

Note: Density 0.280 lb/in.^{3}.

(a) 1500 F preheat, 1875 F 8 min, AQ, temper 1 hr; 0.39C, 0.57Mn, 1.05Si, 3.45Cr, 2.62Mo, 0.38V.[(5)]

(b) 1950 F 30 min, AQ, temper 3 + 3 hr; 0.40C, 0.65Mn, 0.010P, 0.016S, 0.98Si, 3.00Cr, 2.88Mo, 0.32V; ground from 0.109 inch after HT.[(9)]

(c) 1950 F 30 min, AQ, temper 2 + 2 hr; 0.43C, 0.50Mn, 0.77Si, 0.011P, 0.030S, 3.40Cr, 2.50Mo, 0.45V, 52 ppm N_2, 22 ppm O_2, 2.0 ppm H_2.[(8)]

(d) 1950 F 40 min, AQ, temper 3 + 3 hr; 0.38C, 0.57Mn, 1.04Si, 0.009P, 0.008S, 3.31Cr, 2.88Mo, 0.49V, 12ppm N_2, 76 ppm O_2, 1.1 ppm H_2.[(6)]

(e) 1950 F 30 min, AQ, temper 2 + 2 hr; 0.38C, 0.41Mn, 0.93Si, 0.010P, 0.006S, 3.31Cr, 2.55Mo, 0.46V, 38 ppm N_2, 8 ppm O_2, 1.0 ppm H_2.[(6)]

TABLE 11. TENSILE PROPERTIES OF MAR-AGING STEELS[19]

Condition	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C	Yield Strength-Density Ratio, 1000 in.	Tensile Strength-Density Ratio, 1000 in.
	18Ni (250) Sheet, Longitudinal Specimens					
Ann 1500 F, marage 900 F	252	262	4.5		873	908
Ann 1500 F, CR 50%, marage 900 F	286	289	3.5		990	1000
	18Ni (300) Sheet, Longitudinal Specimens					
Ann 1500 F, marage 900 F	280	290	2.0		970	1000
Ann 1500 F, CR 50%, marage 900 F	300	301	3.5		1004	1040
	20Ni Sheet, Longitudinal Specimens					
Ann 1500 F, ref.[a], marage 850 F	256	264	6.0	51	915	943
Ann 1500 F, CR 50%, marage 900 F	273	281	4.0	53	975	1000
	20Ni Sheet, Transverse Specimens					
Ann 1500 F, ref., marage 850 F	261	269	4.5	51	932	960
Ann 1500 F, CR 50%, marage 900 F	279	293	3.7	53	997	1045

Note: Density 18Ni 0.289 lb/in.^{3}, 20Ni 0.280 lb/in.^{3}.

(a) Ref. indicates refrigeration treatment at -100 F for 16 hours.

maraging treatment. The corresponding tensile strength-density ratio is 1,000,000 inches. Although still new, these steels are reported to be readily fabricated and welded in the "annealed" condition. After fabrication and welding, the high strength level can be achieved by the simple aging treatment. An aging furnace for 240-inch-diameter cases, for example, would be considerably less complex than a furnace for austenitizing and quenching treatments that would be required for the other steels. Large furnaces for stress-relieving weldments are in service, and this is the type that would be required.

At the present time, there are a number of research projects for studying the effect of combinations of heat treating plus plastic deformation of alloy steels to achieve specimens and components of higher strength levels than can be achieved by the usual heat-treating procedures. These studies include the processes known as ausforming, marforming, and others. By using these processes under carefully controlled conditions, very high strengths can be obtained in certain alloy steels. In some of these studies, the object is to apply these processes to pressure vessels. To date, results of these latter studies are very limited. The present state of the art has not reached the point where these processes can be considered for use in producing large rocket cases.

FRACTURE TOUGHNESS OF HIGH-STRENGTH STEELS

A lengthy discussion of fracture toughness of rocket-case steels is outside the scope of this report, but it cannot be overlooked in discussing the properties of these steels. A number of testing methods have been proposed for evaluating the fracture toughness or brittle fracturing characteristics of high-strength steel sheet. However, none of these methods has been accepted as standard. Of the proposed specimens intended for tensile loading, the designs include edge-notched and center-slotted specimens as well as specimens with short center cracks through the thickness and center cracks part way through the thickness. Specimens for other methods of loading have also been proposed.

Studies to evaluate the fracture toughness of various alloy steels have been reported by Freymeyer[6,9,10,15,17], March[7,8,11], Srawley[20], Steigerwald[21], and many others. Many factors such as strength level, grain size, melting practice, inclusion rating, thickness, specimen direction in the sheet, and degree of decarburization affect the fracture toughness.

For current commercial alloy steels and heat treatments, there appears to be a maximum relative fracture toughness level (for a given thickness) corresponding to each yield-strength level. This is shown by the points in Figure 1 from a report by Srawley and Beachem[20]. The presence of certain alloying elements in the steels, as well as the factors noted above, influences the positions of the points on this graph. The objective is to achieve a maximum indication of fracture toughness for the specified yield-strength level or to find some means to exceed the present upper limit. It will be noted that the upper limit can be achieved with several types of alloy steels.

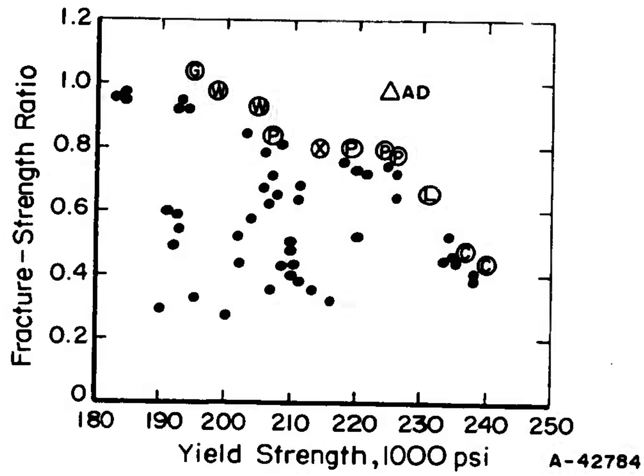

FIGURE 1. FRACTURE-STRENGTH RATIOS VERSUS YIELD STRENGTH FOR SEVERAL COMMERCIAL STEELS AT ROOM TEMPERATURE

(Srawley and Beachem, Reference 20.)

Note: Steel G is Type H-11, Steel P is AMS 6434, Steel X is nonstandard Ni-Cr-Mo-V type, Steel L is nonstandard Cr-Mo-V type, Steel C is AISI 4340 (modified), and Steels W and AD are stainless steels (AD was cold rolled and aged, and point shown is for longitudinal specimens). Steels G, P, X, L, and C were consumable-electrode vacuum melted.

REVIEW OF PRESSURE-VESSEL TESTS

As service stresses in the relatively thin shell of a rocket-motor case are primarily of the biaxial type, a number of the steels listed in Table 1 have been tested as pressure vessels of various sizes, or as subscale motor cases, to evaluate them under biaxial stresses. Data from uniaxial tensile specimens have not been considered a reliable indication of the properties obtained through biaxial stressing. Furthermore, pressure-vessel testing permits an evaluation of other factors such as decarburization, effect of various end-closure contours, welds, mismatch, etc. Usually the pressure vessels are instrumented with strain gages, pressure gages, and associated instrumentation to measure strains in various locations and directions, internal pressures, volumetric changes, etc. Burst tests are very expensive to perform, but results of these tests are needed in order to correlate the data with data from other types of mechanical tests to show the relationships that exist.

Selected data from pressure-vessel tests are presented in Table 12. In general, the data were selected to show the highest or best results for the burst tests in the various series of pressure vessels studied. The data, therefore, show the potential properties that can be achieved for a given steel with a specified heat treatment under biaxial loading. For pressure vessels in a specific series representing one material, fabrication technique, heat treatment, etc., those that failed at stresses substantially lower than the maximum in the series probably failed at the lower stress level because of unexpected flaws, mismatch, or other sources of stress concentration. Data were used as reported even though the basis for yield stresses in the pressure-vessel tests were not necessarily the same. Corrections for such variations have been made by Sachs, Schapiro, and Hoffman in comparing data from a number of the same sources.[33] Consideration of these corrections does not modify the conclusions of this review. Chemical analyses and processing data for the vessels in Table 12 are given in Table 13.

Probably the most interesting data in Table 12 are in the two columns headed Hoop Yield Stress-Yield Strength Ratios and Burst Stress-Tensile Strength Ratios. The required data for calculating these ratios were not given in some instances, but available data are sufficient to illustrate the point. It has been shown theoretically by a number of investigators that, when cylindrical specimens are subjected to internal pressure to obtain biaxial stresses at a 2:1 ratio, the major biaxial stress at the yield strength should be about 1.15 times the uniaxial yield strength, and the maximum stress at bursting load should be about 1.15 times the uniaxial ultimate strength. In some instances, the criterion for biaxial yielding was not exactly comparable to the 0.2 per cent offset yield strength as used in tensile tests. A higher ratio than 1.15 will be obtained for the bursting stress if there is localized plastic bulging before bursting occurs. If there are stress concentrations at flaws, welds, bosses, etc., and fracture starts at one of these locations, it is likely that the ratio based on nominal stresses will be less than 1.15.

As shown in Table 12, these ratios are usually over 1.00 and many of them are within the range 1.10 to 1.20. Ratios within this range are indicative of successful design, fabrication, heat treatment, and inspection of the pressure vessel. It is significant to note that ratios over 1.00 can be obtained with most of the steels listed even when heat treated to high strength levels.

TABLE 12. SELECTED DATA FROM BURST TESTS ON SUBSCALE MOTOR CASES AND PRESSURE VESSELS (UNCLASSIFIED)

See Table 13 for chemical analyses and processing data.

					Tensile Properties			Pressure Test Data								
Steel	Vessel No.	Wall Thickness, inch	Diam, inches	Decarb., inch	Yield Strength (0.2 Offset), 1000 psi	Tensile Strength, 1000 psi	Elong. in 2 In., per cent	Yield Stress, 1000 psi	Burst Hoop Stress, 1000 psi	Hoop Yield Stress-Yield Strength Ratios	Burst Stress-Tensile Strength Ratios	Pressurizing Fluid	Fabrication Method	Number of Vessels Tested of Same Alloy	Company	Reference
4130	L-1	0.094	11.85	0.017	186	226	7	192	234	1.04	1.04	Water	Roll and weld	5	U. S. Steel	22
4137	--	0.050	5.7	--	220	228	--	205	248			--	Deep drawn	3	Mellon	23
4140	CSP-3	0.10	11.65	0.008	196	241	8	234.5	269	1.20	1.12	Water	Deep drawn	4	Naval Weapons Plant	24
4330 V (Mod + Si)	2-8	0.090	3.7	--	206	255	--	181.6	258.6	0.88	1.01			2	Frankford Arsenal	25
4340	F-13	0.05	2.0	--				256	295				Machined from bar	2	Space Tech. Lab.	26
	A-12	0.049	2.0	--				244	277				Machined from bar	3	Space Tech. Lab.	26
AMS 6434	DSP-4	0.10	11.65	0.010	178	197	6	216	245.5	1.16	1.10	Water	Deep drawn	4	Naval Weapons Plant	24
300-M	M-1	0.077	11.82	0.016	216	261	5	240	267	1.11	1.02	Water	Roll and weld	5	U. S. Steel	22
	--	0.062	9.4	0.007	244	290	6	--	329	--	1.13		Girth weld		Pratt & Whitney	27
MBMC No. 1	BSP-8	0.10	11.65	0.011	216	253	5.5	253	281	1.17	1.10	Water	Deep drawn	4	Naval Weapons Plant	24
	B-1	0.081	11.85	0.018	204	243	5	226	252	1.11	1.04	Water	Roll and weld	5	U. S. Steel	22
		0.055	16	0.011	237	280	5.2	--	318	--	1.14	Water	Forged and spun	32	Borg-Warner	28
		0.047	16	0.004	240	271	5.5	--	289	--	1.07	Water	Roll and weld	23	Borg-Warner	28
Airsteel X200	X-1	0.072	11.84	0.018	215	259	5	237	278	1.10	1.07	Water	Roll and weld	5	U. S. Steel	22
4137Co (UCX-2)	--	0.050	5.7	--	240+	283	5.5	246	275	1.02	0.97		Deep drawn, no welds	3	Mellon	23
		0.100	12.0	--	236	279	5.5	--	286	--	1.02		Roll and weld	1	Mellon	23
		0.100	12.0	--	248	291	7.5	--	291	--	1.00		Roll and weld	1	Mellon	23
Rocoloy 270	--	0.080	3.5	0.011	265	308	8.6	--	275	--	0.89		Cold drawn and spun		Mellon	
Ladish D-6ac	--	0.043	9.4	0.003-0.007	243	277	5	--	326	--	1.18		Girth weld		Pratt & Whitney	27
	L-S	0.05	2.0	--				271	309				Fmm extruded forging	3	Space Tech. Lab.	26
	R-11	0.05	2.0	--				255	280				Fmm extruded forging	3	Space Tech. Lab.	26
	S-8	0.05	2.0	--				269	311				Fmm extruded forging	2	Space Tech. Lab.	28
	6749	--	10	--	220	270	5	286	322	1.30	1.19		Forge-extruded	2	Aerojet-General	29
	6737	--	10	--	218	235	7.5	240	257	1.10	1.09		Forge-extruded	2	Aerojet-General	29
	6365	--	24	--	229	264	7	None	235	--	0.89		Forge-extruded, ring rolled	2	Aerojet-General	29
	6366	--	24	--	201	222	8.5	248	264	1.23	1.19		Forge-extruded, ring milled	2	Aerojet-General	29
H-11	ASP-4	0.10	11.65	0.008	211	255	6.5	248	279	1.18	1.08	Water	Deep drawn	4	Naval Weapons Plant	23
	H-4	0.085	11.84	0.006	244	297	5	259	260	1.06	0.88	Water	Roll and weld	5	U. S. Steel	22
	--	0.065	9.4	0.0005	241	291	5	--	354	--	1.21		Flow turned		Pratt & Whitney	27
	48-R	0.050	6	--	226	255	--	--	284	--	1.11	Water	Roll and weld	78	Solar Aircraft	30
	--	0.050	5.7	--	230+	286	--	191	312	--	1.09	--	Deep drawn	3	Mellon	23
	--	0.050	5.7	--	220+	263	--	188	308	0.88	1.17	--	Deep drawn	3	Mellon	23
	--	0.050	5.7	--	210+	243	--	182	287	0.87	1.18	--	Deep drawn	3	Mellon	23
25% Ni		0.070	6	--	245	259	7	280	314	1.14	1.21	--	Forged, machined, H.T.	2	Curtiss-Wright	31
18% Ni (250)			6	--	--	290*	--	--	324	--	1.12	--	Forged, machined, welded	2	Curtiss-Wright	32
Type 301	A-48	0.059	12.5	--	--	275	--	--	284	--	1.03	Water	Roll, weld, stretch at -320 F, and age at 800 F	15	ARDE-Portland	
	N-10	0.054	12.5	--	--	--	--	--	281	--	--	Water	Roll, weld, stretch at -320 F and age at 500 F	4	ARDE-Portland	

*Assumed value.

TABLE 13. CHEMICAL ANALYSES AND PROCESSING DATA FOR STEELS IN TABLE 12

Steel	Vessel No.	Melting Method	Chemical Analyses, per cent by weight: C	Mn	P	S	Si	Ni	Cr	Mo	V	Others	Heat Treatment: Austenitizing Temp, F	Austenitizing Time, minutes	Quench	Tempering Temp, F	Tempering Time, hours	Remarks
4130	L-1	Standard	0.32	0.47	0.009	0.012	0.23		1.00	0.16			1625	60	Salt at 400 F	400	2	
4137	--	No additional data																
4140	CSP-3	Standard	0.40	0.81	0.014	0.013	0.22	0.35	0.66	0.22			1550	120	Oil	450	2 + 2	H. T. in salt
4330 V (Mod. + Si)	2-B	Standard	0.30-0.35*	0.75-1.0			1.4-1.7	1.5-2.0	0.8-1.0	0.4-0.6	0.8-0.12		1625	--	Oil	600	--	
4340	F-13	Standard	0.39	0.71			0.30	0.78	0.71	0.20			1525	10	Oil	400	4	53.1 R_C
	A-12	Standard	0.39	0.71			0.30	0.78	0.71	0.20			1525	10	Oil	475	4	50.2 R_C
AMS 6434	DSP-4	Standard	0.35	0.68	0.013	0.010	0.24	1.64	0.77	0.42	0.29		1600	120	Oil	450	2 + 2	H. T. in salt
300-M	M-1	Standard	0.40	0.80	0.009	0.009	1.48	1.72	0.83	0.37	0.11		1600	60	Salt at 400 F	600	2 + 2	
		Standard	0.40	0.80	0.009	0.009	1.48	1.72	0.83	0.37	0.11		1650	30	Air, -100 F 2 hr	550	2	
MBMC No. 1	BSP-8	Standard	0.44	0.84	0.010	0.015	1.72	0.39	0.72	0.20	0.02		1600	120	Oil	600	2 + 2	H. T. in salt
	B-1	Standard	0.39	0.79	0.016	0.016	1.68	--	0.80	--	0.05		1600	60	Oil	600	1	
			0.42	0.80	0.015	0.007	1.65	--	0.75	--	0.07		1600	65	Oil	600	3	
			0.425	0.76	0.019	0.020	1.42	--	0.76	--	0.08		1600	65	Oil	600	3	
Airsteel X200	X-1	Standard	0.40	0.99	0.010	0.010	1.41		1.98	0.40	0.07		1750	30	Air	700	1/2	
4137 Co (UCX-2)	--		0.39*	0.70	0.010	0.010	1.0		1.10	0.25	0.15	1.0 Co	1700	30-45	Oil	560	Twice	
			0.39*	0.70	0.010	0.010	1.0		1.10	0.25	0.15	1.0 Co	1700	30-45	Oil	550	Twice	
			0.39*	0.70	0.010	0.010	1.0		1.10	0.25	0.15	1.0 Co	1700	30-45	Salt at 400 F	550	Twice	
Rocoloy 270		Vac. arc	0.39-0.45(a)	0.4-0.8	0.013 max.	0.013 max.	0.9-1.3	0.7-1.1	1.1-1.6	0.4-0.6	0.1-0.2	0.2-0.5 W, 1.2-1.5 Co	1730	--	Oil	700	--	

TABLE 13. (Continued)

Steel	Vessel No.	Melting Method	Chemical Analyses, per cent by weight: C	Mn	P	S	Si	Ni	Cr	Mo	V	Others	Heat Treatment: Austenitizing: Temp, F	Austenitizing: Time, minutes	Quench	Tempering: Temp, F	Tempering: Time, hours	Remarks
Ladish	--												1650	30	Air	600	2 + 2	
D-6a	L-5	Vac. arc	0.46	0.74			0.28	0.44	1.10	0.86	0.05		1550	45	Forced air	400	4	52.4 R_C
	R-11	Vac. arc	0.46	0.74			0.28	0.44	1.10	0.86	0.05		1550	45	Forced air	600	4	49.9 R_C
	S-8	Vac. arc	0.46	0.74			0.28	0.44	1.10	0.86	0.05		1550	45	Salt at 400 F	400	4	53.3 R_C
	6749	Vac. arc	0.43	0.71	0.006	0.007	0.24	0.51	0.98	1.09	0.08		1650-1550	30 + 30	Salt at 400 F	600	--	--
	6737	Vac. arc	0.43	0.71	0.006	0.007	0.24	0.51	0.98	1.09	0.08		1650-1550	30 + 30	Salt at 400 F	950	--	48.0 R_C
	6365	Vac. arc	--										1650-1550	30 + 30	Salt at 400 F	600	--	49.0 R_C
	6366	Vac. arc	--										1650-1550	30 + 30	Salt at 400 F	950	--	47.0 R_C
H-11	ASP-4	Standard	0.38	0.43	0.012	0.012	1.08	0.08	5.02	1.35	0.45		1850	120	Air	1000	2 + 2 +2	H. T. in salt
	H-4	Standard	0.41	0.44	0.009	0.006	0.91		5.29	1.36	0.51		1850	60	Air	1000	2 + 2	1025 F, 2 hr
	--																	
	48-R	Standard	0.040(a)	0.30	0.010	0.010	0.90		5.00	1.30	0.50		1850	60	Air	?	Twice	51 R_C
	--		0.040(a)	0.30	0.010	0.010	0.90		5.00	1.30	0.50		1850	60	Air	?	Twice	51 R_C
	--		0.040(a)	0.30	0.010	0.010	0.90		5.00	1.30	0.50		1850	60	Air	?	Twice	51 R_C
	--		0.040(a)	0.30	0.010	0.010	0.90		5.00	1.30	0.50		1850	60	Air	?	Twice	51 R_C
25% Ni			0.03	0.011			<0.01	24.4				1.7Ti, 0.23Al, 0.41Cb	1500	60	Air	--	--	1300 F 4 hr. -100 F, 900 F 1 hr
18% Ni (250)			0.03	0.011			<0.01	24.4					--	--	--	900	3	Aging after forging and welding
Type 301	A-48	Standard	0.060	1.56				7.60	17.36				None					Aged 800 F
	N-10	Standard	0.055	1.52				7.50	17.02				None					Aged 500 F 20 hr

(a) Nominal composition or range.

Additional burst-test data to show the effect of testing temperature are presented in Table 14. Results of these tests over the temperature range from -160 to 365 F also show the effect of biaxial strengthening (burst strength-tensile strength ratios over 1.00). Of particular interest are the data on the per cent of shear fracture. At the lower temperatures, the relative amount of shear was as low as 73 per cent, indicating as much as 27 per cent flat brittle fracture. These data provide the upper portion of burst-test transition-temperature curves based on per cent shear in the fracture. At lower test temperatures, the percentage of brittle fracture would increase and eventually the pressure vessels would become embrittled to the point where the burst hoop stress would be less than the uniaxial tensile strength at the same temperature.

This discussion leads to the conclusion that the particular alloy steel selected for a given rocket system is not so important as certain other factors so long as the steel has the following characteristics:

(1) Minimum carbon content consistent with desired strength level

(2) Sufficient hardenability to harden throughout

(3) Can be tempered to the desired strength level without encountering an embrittling effect

(4) Can be tempered to the desired strength level at a sufficiently high temperature to give at least partial residual stress relief and transformation of most of the retained austenite

(5) Free of gross inclusions that might initiate brittle fracture

(6) Satisfactory weldability without tendency to develop welding cracks or flaws

(7) Minimum distortion during welding and heat treating

(8) Adequate fracture toughness for the intended application.

There is evidence to indicate that the load carrying-ability of a 4340 steel specimen having a small flaw is not the same as for a similar specimen of H-11 steel having a similar flaw and heat treated to the same strength level. The point is that under certain circumstances, steels at the same strength level but of different compositions do show different characteristics. These differences are not to be overlooked in selecting a high-strength steel or steels for rocket-motor cases. Melting technique is also important from the standpoint of toughness at high strength levels. Furthermore, the environment (moisture in the air), exposure temperature, and fluid used in pressurizing the pressure vessels are factors that can affect the results of the pressure-vessel tests as well as of service performance.

In the fifth column of Table 12, depth of decarburization is given as indicated by superficial hardness measurements across a polished cross section of a heat-treated specimen corresponding to the material in the pressure vessel. It is doubtful that all of the investigators used the same technique but most of the investigators have realized that

TABLE 14. EFFECT OF TESTING TEMPERATURE ON BURST-TEST DATA FOR MODEL PRESSURE VESSELS (UNCLASSIFIED)[34]

						Tensile Properties			Pressure Test Data			Heat Treatment				
												Austenitizing				
Steel	Test Temp, F	Vessel No.	Wall Thickness, inch	Diam, inches	Decarb., inch	Yield Strength (0.2% Offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 In., per cent	Burst Hoop Stress, 1000 psi	Shear in Fracture, per cent	Burst Stress-Tensile Strength Ratio	Temp, F	Time, minutes	Quench	Tempering Temp, F	No. of Vessels Tested at Same Temperature
4130	-160	--	0.105	5.21		198	210	5.5	235	75	1.12	1700	68	Oil	825	1
	-105	(a)	0.105	5.21		192	212	4.8	230	90	1.09					3
	-5	--	0.105	5.21					221.5	100	--					1
	6	--	0.105	5.21					221.5	100	--					1
	75	(a)	0.105	5.21		185	201	4.5	223.7	100	1.11					3
	200	(a)	0.105	5.21					213	100	--					3
	365	(a)	0.105	5.21		167	193	5.0	207	100	1.07					3
4130	-105	(a)	0.105	5.21					308	73	--	1700	68	Oil	400	3
	80	(a)	0.105	5.21		206	238	6.0	299.7	95	1.25					3
4340	-105	(a)	0.095	3.52	0.001-0.022				284.5	88	--	1600	--	Oil	425	7
	-20	(a)	0.095	3.52	0.002-0.030				292	93	--					6
	75	(a)	0.095	3.52	0.002-0.022		240-262		274	94	1.05-1.14					6

(a) Average data for all corresponding specimens.

All pressure vessels were produced by drawing and spinning. The 4340 steel was vacuum melted. Chemical analysis for several of the 4340 steel vessels was <0.01P, 0.007S, 106-129 ppm N_2, 25-65 ppm O_2, 2.2-3.7 ppm H_2

Limited data on D6ac steel pressure vessels of 34.5 diameter tested at ambient temperature and 340 F in Reference 35.

this is a factor and have measured it. Investigators at Pratt & Whitney and at other laboratories have studied the effect of partial surface decarburization and have found that a controlled partially decarburized surface layer of limited depth is practically necessary in obtaining burst stress-tensile strength ratios over 1.00. The optimum amount of decarburization has very little if any effect on the tensile properties.

From this discussion, it is evident that there is much that can be done to optimize the results of the burst tests and performance. Freedom from flaws, storage in a dry environment, use of oil rather than water for pressurizing, maintenance of the temperature at the specified level (preferably not too cold), production of a partially decarburized surface layer during heat treating, etc., can improve results of pressure testing. The method of mechanical support of the pressure vessel during pressure testing also can be a factor.

In comparing the fabrication methods with burst stress – tensile stress ratios in Table 12, it appears that the ratios for vessels produced by the roll-and-weld technique are often over 1.00, but the ratios for the deep-drawn and power-roll-formed vessels may be higher in some instances. The data are not conclusive, but this is an interesting comparison to follow since the roll-and-weld technique will be required in the initial fabrication of the large motor cases of 120-inch diameter and over.

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